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Trends in Control of NC Machines

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Abstract

The paper comments on the new possibilities of utilizing the inertial navigation system in robototechnics. It deals with the application of a new inertial measurement system for a robotic workplace calibration. The calibration is necessary so that the simulation model of the production device can adjust to the real geometric conditions. The aim is to investigate and develop a new combined inertial navigation system based on electronic gyroscopes, magnetic and barometric sensors. The crucial activity is focused on three basic fields: 1. the first goal is to analyze accelerometer and gyroscopic sensors and their possibilities of utilization for inertial navigation. The simulation of the effect of sensors with different metrological parameters and their effect on the properties of the proposed combined navigation system, 2. the second goal is to optimize a specialized processor system for processing the data from the defined sensors in connection with controlling items of an industrial robot. The proposal of an algorithm of combined navigation with respect to the used processor system and 3. the third goal is to verify experimentally the proposed inertial navigation system in real conditions of the industrial robot operation.

Keywords: inertial navigation system; sensors; control system; robot; processor system; machines operations.

1. Introduction

Current needs of production technology place requirements on the application of mechanization, automation and robotization of the production process. It is not so long ago when the industrial robots were implemented into less demanding working environments determined for manipulation operations while taking over the command and synchronizing the activities of individual production devices and technology. At present, the requirements for the product quality and quantity, for new complex technological procedures as well as for constructing the complex technological mechanisms are very demanding and still increasing. To meet these requirements the elaboration of new technological procedures is not sufficient. The design, development and construction of new automated and robotic devices and their modernization are needed.

One of the important robot properties implemented in the production technology is represented by their accuracy and reliability related to their capability execute a precisely defined procedure, motion in/on the programmed trajectory or other spatial operations. Current spatial demands as well as the efficient utilization of the space make the robot often operate in constricted conditions. The motion of the tool or manipulation with components requires maximum accuracy. The industrial robots they are position sensors that are used to determine the current position of robot´s parts (gripper, arm) and for the measurement of the position without calibration preparations the following is used:

- photogrammetric methods – allowing the measurements of dynamic objects,
- geodetic methods – allowing the measurements of static objects.

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Obviously, this leads to really high requirements for appropriate calibration of the robotic device as the robots´ collisions, their mechanical damage frequently occur and the production line has to be stopped and the production losses grow [1,2,3].

Continuous assessment of the controlled and navigated robot using the sensors for motion detection, i.e. gyroscopes and accelerometers can be ensured by inertial navigation. Via the navigation computer and data obtained from the motion detectors the position, orientation as well as the direction can be constantly determined without using external information sources. The current position of the object is assessed on the basis of knowing the initial position and subsequent continual measurement of acceleration and direction of the motion in the reference system. The inertial navigation principle is based on Newton´s laws expressing the motion change at using the external forces as well as the acceleration which is proportional to the orientation and size of the external force.

2. Inertial navigation system

Currently, for the 3D inertial navigation execution the inertial navigation system (INS) is used and you can encounter it on the board of army or civil aeroplanes where it is the primary source of navigation information. INS includes one navigation computer at minimum and a platform or module comprising accelerometers and gyroscopes. The reason to use INS for navigation is its autonomy and impossibility of purposeful interrupting its operation from the outside. The sensors of acceleration (accelerometers) as well as the sensors of angular velocity (gyroscopes) are firmly attached to the platform connected the navigated means [4,5].

The basic element INS is represented by IMU, Inertial Measurement Unit. Sensors whose outcome is influenced only by object motion on which the IMU is located are considered as primary sensors of IMU. These primary sensors in the inertial navigation are used for n are represented by angular velocity/speed sensors whose output signals after integration are used for the determination of orientation in space and the accelerometers whose output signals after precise compensating the gravitation acceleration and Coriolis force can be integrated into the velocity and position. Platform-free systems have the sensors located into the 3D coordinate system so that each axis of the navigated object corresponds to the accelerometer´s sensitivity axis as well as to the angular velocity sensor. Such an inertial measurement unit has six degrees of freedom, i.e. it allows the measurement of transaction and rotation movements in three-orthogonal axes. The inertial sensors accuracy is of key significance in the autonomous navigation.

For less demanding applications we can utilize cheaper IMU whose lower accuracy is compensated by the implementation into integrated navigation systems in which the required velocity is acquired by the integration of navigation information from several navigation systems. The navigation computer is the core of the inertial navigation system. The navigation computer processes measured data from the inertial measurement unit and prepares information on the angular position, velocity and the navigated object position on the bases of known initial conditions. The measured data from gyroscopes represent the navigated object vector against the inertial coordinate system indicated by index „i“ and measured in the individual axes of Cartesian coordinate system of the navigated object indicated by „b“.

$$\omega_{ib}^{b} = \left[\omega_{ib}^{bx}, \omega_{ib}^{by}, \omega_{ib}^{bz}\right]^T \tag{1}$$

Via mathematical adjustments and integration of angular velocity/speed we obtain the information on the angular position of the navigated object against the reference system (incline) (náklon). The data measured by three-component accelerometer represent the vector of acceleration measured in the navigated object axes.

$$a^{b} = \left[a^{bx}, a^{by}, a^{bz}\right]^T \tag{2}$$

After the primary processing these data are transformed into the reference system, compensation by gravity and Coriolis acceleration are executed and subsequently, double integration is carried out. By the first integration the information on the navigated object velocity/speed is obtained and by the other one the information on the object position.

Eq. 3 represents the mathematical model of INS operating in the navigation coordinate system, i.e. the selected reference system is navigation one with the orientation of axes to North-East-Down [6].

$$\begin{bmatrix} \dot{r}^n \\ \dot{v}_E^n \\ \dot{C}_b^n \end{bmatrix} = \begin{bmatrix} v_E^n \\ C_b^n \cdot a^b - \left(2 \cdot \Omega_{ie}^n + \Omega_{en}^n\right) \cdot v_E^n + g^n - \Omega_{ie}^n \cdot \Omega_{ie}^n \cdot r^n \\ C_b^n \cdot \left[\left(\omega_{ib}^b - C_n^b \cdot \left(\omega_{en}^n + C_e^n \cdot \omega_{ie}^e\right)\right) \times\right] \end{bmatrix} \tag{3}$$

where

$r^n = \left[x^n, y^n, z^n\right]^T$ - position vector in navigation coordinate system,

$v^n = [v^{nx}, v^{ny}, v^{nz}]^T$ - velocity vector in navigation coordinate system,
g^n - gravity acceleration vector in navigation coordinate system,
a^b - acceleration measured by accelerometers in the coordinate system of the navigated object,
ω_{ib}^b - angular velocity between the coordinate system of the navigated object and inertial coordinate system measured by gyroscopes in the coordinate system of the navigated object,
C_b^n - transformation matrix of the navigated object coordinate system into navigation coordinate system,
$\Omega_{ie}^n = [\omega_{ie}^n \times]$ - anti-symmetric matrix of angular velocity between the Earth coordinate system and inertial coordinate system expressed in navigation coordinate system,
$\Omega_{en}^n = [\omega_{en}^n \times]$ - anti-symmetric matrix of angular velocity between the Earth coordinate system and navigation coordinate system expressed in navigation coordinate system.

Vectors of $r^n, \dot{r}^n = v_E^n, \dot{v}_E^n$ in Eq. 3 are expressed in Cartesian coordinates (e.g. $[x^n, y^n, z^n]$ (orientation North-East-Down)). The other possible approach is represented by expressing these vectors in coordinates as follows: $r^n = [\lambda, \varphi, h]^T$ (longitude, latitude and height above the reference ellipsoid). Their mutual relation can be expressed by the transformation

$$v_E^n = \begin{bmatrix} v_E^{nx} \\ v_E^{ny} \\ v_E^{nz} \end{bmatrix} = \begin{bmatrix} 0 & R_M + h & 0 \\ (R_N + h)\cdot\cos\varphi & 0 & 0 \\ 0 & 0 & -1 \end{bmatrix} \cdot \begin{bmatrix} \lambda \\ \varphi \\ h \end{bmatrix} \tag{4}$$

where R_N, R_M – are the radiuses of Earth curvature.
Opposite transformation is as follows

$$\dot{r}^n = \begin{bmatrix} \dot{\lambda} \\ \dot{\varphi} \\ \dot{h} \end{bmatrix} = \begin{bmatrix} 0 & \dfrac{1}{(R_N + h)\cdot\cos\varphi} & 0 \\ \dfrac{1}{R_M + h} & 0 & 0 \\ 0 & 0 & -1 \end{bmatrix} \cdot \begin{bmatrix} v_E^{nx} \\ v_E^{ny} \\ v_E^{nz} \end{bmatrix} \tag{5}$$

If we apply Eq. 5 to Eq. 3 we obtain the result navigation equations

$$\begin{bmatrix} \dot{r}^n \\ \dot{v}_E^n \\ \dot{C}_b^n \end{bmatrix} = \begin{bmatrix} D^{-1}\cdot v_E^n \\ C_b^n \cdot a^b - (2\cdot\Omega_{ie}^n + \Omega_{en}^n)\cdot v_E^n + g^n - \Omega_{ie}^n \cdot \Omega_{ie}^n \cdot r^n \\ C_b^n \cdot [(\omega_{ib}^b - C_n^b \cdot (\omega_{en}^n + C_e^n \cdot \omega_{ie}^e))\times] \end{bmatrix} \tag{6}$$

where

$$D^{-1} = \begin{bmatrix} 0 & \dfrac{1}{(R_N + h)\cdot\cos\varphi} & 0 \\ \dfrac{1}{R_M + h} & 0 & 0 \\ 0 & 0 & -1 \end{bmatrix} \tag{7}$$

3. Implementation of inertial navigation system into robots operation

For industrial robots the orientation, or precise determination of the programmed point in space is the necessary condition for their moving without collision or accident which is essential not only of a robotic device but of the running process as well. Currently, when for increasing the reliability of robotized workplaces operation in the production technology comes into consideration the main orientation is on integrating the inertial navigation systems into the control process and operation control of robotic as well as other peripheral means of production systems.

A new and not researched control method of robots´ trajectory as well as of other means and components in production so far is represented by utilizing inertial navigation systems on the basis of hybrid MEMS (micro-electro-mechanic-systems) sensors which appeared not long ago. The research in INS is running in several branches of industry related to aviation, rockets, ships, however, nobody has researched these systems implemented in the field of control neither control of industrial robots in real time [7,8].

Inertial navigation system consists of a measurement unit comprising gyroscopes rotating around three axes X, Y, Z, then three accelerometers operating in these axes X, Y, Z (Fig. 1) and a navigation computer assessing data obtained from measurement devices/instruments.

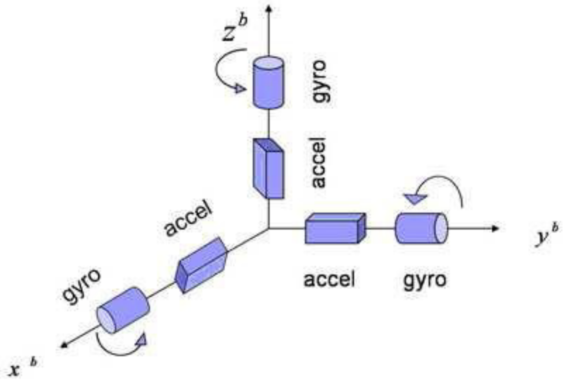

Fig. 1. Basic principle of INS measurement unit.

The basis is represented by the system of autonomous robot´s trajectory control aimed at the prevention of collisions. In the new concept, the control of the current position is dealt with by the autonomous system of accelerometers and gyroscopes in three axes. Another progressive method, not frequently used so far, is the utilization of INS in the system of robot´s trajectory control. If the robot´s position is not calibrated on a regular basis, the deviation will continuously increase and big differences between the real robot´s position and programmed position can grow which is unacceptable for practice.

The navigation autonomy, i.e. independence on external sources of navigation information was the main reason for INS implementation. In contrast to all other navigation systems the inertial navigation is completely self-sufficient and independent on external environment, i.e. the system can resist external influences such as magnetic faults, electronic disturbances and signal deformation.

If we implement INS as an independent control into the robot´s control system, the programmed position will be constantly compared to its real position in the working environment. Thus, the robot´s position will be continuously checked and calibrated via the navigation computer. The deviation does not grow and there are no differences between the real and programmed positions of the robot.

Fig. 2 shows concept block scheme of INS implementation into the control of a technological robot in general [9].

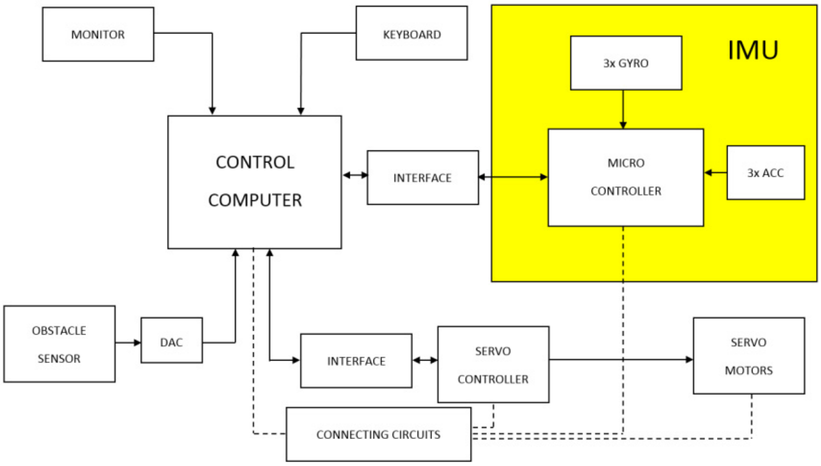

Fig. 2. Concept block scheme of a robot with integrated inertial system. [2]

Microcontroller processes the analogues signal from the sensors via ADC ports and converts them into a digital signal. To meet the requirement of the control computer the data processed this way are sent through the interface to the input/output port. The control computer as a primary unit of implementation assesses the obtained data on the arm position. The robot can operate in a manual regime when the control computer processes and executes the orders of robot´s operation. Manual control is possible by assigning the individual orders via keyboard. In this regime the data from IMU are processed as well and are stored in the base determined. I tis possible to process the data from this base further as well as compare them to live data from IMU and this causes the automated robot´s navigation [10].

Regarding the processed data in the automated regime or the data from the keyboard, the control computer sends a signal to servomotors. The signals are accepted by a servo controller via the interface processing the data and setting up the individual servomotors into motion according to the needs.

The other essential part of the scheme is represented by the obstacles sensors. Particularly, their systematic arrangement on the robot´s arm is important so that it is possible to detect any emerging collision with another object. These sensors constantly transmit a signal into the space (sound, light, etc.). If the signal reflects back to the sensor, it means that in the robot´s surroundings there is and obstacle. The control computer continuously processes the data from the sensors via a digital-analogue converter. If it finds the obstacle it redirects the robot so that the robot avoids it. The sensors detect the obstacle in the distance of 5cm which is sufficient for early alert on collision situation.

Fig. 3 shows robot 1 controlled by the central computer 2. In the place of robot 1 which is prior defined the autonomous system INS 3 is located and is connected to the navigation computer 4 which is connected via the series peripheral interface SPI 5 to the central computer 2. This way it is possible to continuously control the trajectory as well as the position of the observed point in the working environment of the robot 1.

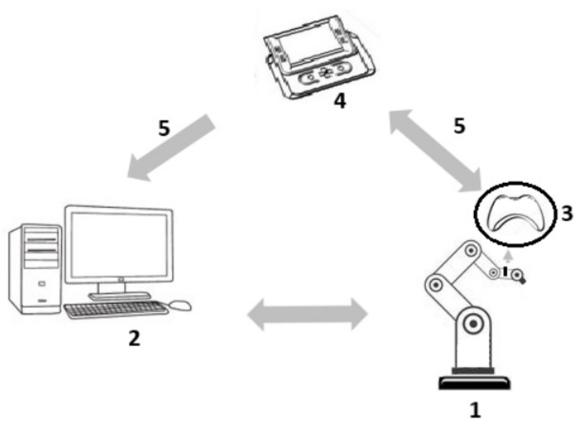

Fig. 3. Implementation of the robot´s autonomous trajectory control.
1 – robot, 2 – central computer, 3 – inertial navigation system,
4 – navigation computer, 5 – series interface

If the initial position of robot 1 is defined, the initial position of INS 3 attached to the robot 1 is defined as well. The motion and current position of robot 1 controlled by the central computer 2 in the working environment is continuously checked and compared to the data of the autonomous INS system 3 about the position by the navigation computer 4 via the series peripheral interface 5.

The navigation computer 4 validates the immediate position of robot 1 and by means of the series SPI peripheral interface 5 it communicates with the central computer 2 making thus the position of robot 1 more precise. This way the robot´s position is constantly assessed and specified by autonomous INS. We speak about Reverse Validation [11,12].

Once the autonomous INS system is applied in the system, no position sensors are necessary. During the repetitive motions robot 1 records the position deflections to the programmed position exponentially growing with the operation time. To minimize the measurement deflections, it is necessary to carry out the continuous calibration of the robot´s position by the system of autonomous control of the robot´s trajectory. When we deploy the autonomous INS system into the control system of robot 1, the calibration is not needed since the autonomous INS system constantly communicates with the navigation computer 4 via the series SPI peripheral interface 5. The central computer 2 assesses the data from the navigation computer 4 and compares them to the data form the control program. Then by the evaluation of the differences in data, it immediately declines the deflection to minimum in real time.

4. Summary

The system of autonomous control of the robot´s trajectory can be used for the determination of the precise robot´s position in its working environment. The application can be used for the robotized workplace calibration. Nevertheless, an absolute correspondence with reality cannot be presumed. The reality deviations from the simulation origin due to various reasons (workpiece position, tool geometric accuracy, and mutual position of robot´s axes). The implemented INS will be used for the calibration without using calibration preparations, i.e. an excellent calibration simplification in practice [13]. The practical example of utilizing the autonomous control system of robot´s trajectory with INS implementation is represented e.g. by robots calibration or solution to the collision states in the production. The autonomy of INS is its significant advantage particularly when compared to other current methods. This leads to a considerable calibration simplification and it can even provide great opportunities in the field of control and measurement.

The contribution represents the original way of controlling the production system industrial robot by the inertial navigation system. Sensors of position are used in classical industrial robots for determining the actual position of their parts (gripper, arm). The inertial system is responsible for determining the actual position in the described system of controlling the robot. Regular adjusting the deflection of sensors – calibration is a necessary condition for the correct activity of the inertial system. If the condition was not fulfilled, the deflection would constantly grow and big differences between the real position of the robot and the position given by the inertial system would appear. In practice it is inadmissible. Inertial systems are being constantly developed therefore by improving the sensors, mainly by minimizing the errors of accelerometers and gyroscopes, more perfect and accurate inertial systems appear.

The possibilities of utilizing the inertial systems are directly proportional to the advance in their development. The ability of precise measuring the position of the robot mainly in necessarily regularly repetitive calibration is increased by this. The implemented INS is able to measure accelerating and slewing the watched point of the arm and to use it for determining the position of the robotic arm in space.

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